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RADC-TDR-62-208

June 19, 1961 to December 19, 1961

ULTRA HIGH POWER TRANSMISSION LINE TECHNIQUES

Prepared by:

Dr. Meyer Gilden

Approved by:

Dr. Lawrence Gould

MICROWAVE ASSOCIATES, INC.
Burlington, Massachusetts

First Technical Note

Contract No. AF30(602)-2545

Prepared
for
Rome Air Development Center
Air Force Systems Command
United States Air Force

Griffiss Air Force Base
New York

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ABSTRACT

This work treats the failure mechanism in microwave transmission lines at ultra-high power levels. Electrical breakdown under non-uniform conditions is discussed. The discussion includes the application of the variational technique for solving the diffusion equation and also includes the derivation of an additional term for the diffusion equation to account for non-uniformities in the gas density. As part of the non-uniform electric field problem, expressions are derived for an idealized rough surface. As part of the more general effects of non-uniform conditions it is shown that a small foreign body in a waveguide can become extremely hot and cause reductions in peak power breakdown thresholds of approximately 5:1. An analysis of the cooling capabilities of an internal gas flow in a waveguide shows that under restricted conditions the power dissipation can be increased by a factor of two or three. Finally the characteristics of a mode suppression filter of oversized, large wave length, rectangular waveguide is derived and discussed.

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I. INTRODUCTION

A. Purpose

The purpose of this program is to study failure mechanisms in microwave transmission lines for ultra-high power microwave systems. In this context ultra-high power indicates values of peak power and average power that cannot be transmitted by the standard waveguides in present use. In general, because of the nature of the failure mechanisms, one cannot speak of peak power or average power limitations independently; the two are inter-related. More specifically high average power can result in significant reduction in the peak power which a system can handle. By obtaining a better understanding of the dependence of the failure mechanisms on the environment in the waveguide and the structure of the waveguide it is hoped that this program will lead to practical solutions of some of the ultra-high power problems. This program is concerned with transmission lines and associated components for frequencies in the range from 1 to 35 kmc.

B. Scope of the Work

The problems which arise in considering ultra-high power failure mechanisms include electrical breakdown, excessive heating, the nature of the microwave arc (once it is formed in the waveguide), and the transmission characteristics of the necessarily over-sized waveguide structures. Electrical breakdown in uniform fields or slightly non-uniform fields has been studied extensively at microwave frequencies. In this program breakdown theory and experiment shall be extended to

cover more sever non-uniform conditions. For example, spacial variations of the electric field near small discontinuities constitutes a non-uniformity which alters the threshold for breakdown. Another example of a non-uniformity is the spacial variation of gas density that arises from temperature gradients which are found, for example, at an excessively hot waveguide window or at a small foreign body. The effect of these non-uniformities in electric field and gas density on electrical breakdown are dependent also upon the gas fill. Although something is known about breakdown and non-uniformities when air is used, there have been no similar studies at microwave frequencies with high dielectric strength gases such as SF_6 or Freon 12. Evidence of this lack of understanding of the nature of these high dielectric strength gases can be found in the experience with current microwave systems where expected improvements from pressurization are not fully realized.

The rise of waveguide temperature has been analyzed for smooth waveguides and waveguides with cooling fins; however, even more pertinent with respect to failures at ultra-high power levels is the matter of localized heating. Knowledge of localized heating is a prerequisite to finding the breakdown threshold. Examples mentioned above included the microwave window which is used in connection with pressurization or evacuation. The temperature rise of the window tends to deplete the gas density in the immediate vicinity thus lowering the breakdown threshold of the entire system. The second example concerned small foreign bodies such as dirt or pieces of rubber or

metal which may be found in the waveguide. In extreme cases these foreign bodies may simply be dust floating around in the waveguide. Here also the elevated temperature decreases the local gas density with the result that the system breakdown threshold is lowered. These problems in heat transfer are important because the levels of temperatures can be high enough to cause reductions of ten to one in the breakdown thresholds.

The nature of a microwave arc once it has been formed in the waveguide is an important aspect of the failure problem. While intermittent arcing may not cause serious damage to the transmission line, a heavy continuous arc once formed may not only damage the transmission line but also result in destroying the vacuum window of the ultra-high power tube. The items of importance which govern the nature of the arc including its movement, are gas fill, the signal characteristics, and the surface conditions of the waveguide itself.

The necessarily over-sized waveguide for ultra-high power brings up a number of problems. One of the first problems is the design of mode suppression filters which remove or prevent the undesired modes of propagation while allowing the desired mode to propagate relatively uneffected. An auxilliary problem is the removal of heat that arises from both the attenuation of the main mode of propagation as well as the absorption of the unwanted modes of propagation.

These four areas of interest can be treated in general without regard to size or frequency of operation since there is no significant change in the breakdown theory or microwave loss theory over the range

of frequencies from 1 to 35 kmc. However, in the physical realization of the systems, practical considerations may dictate quite different approaches. Examples of items which must be considered include, strength of the waveguide, efficient cooling techniques, materials, surface conditions and fabrication techniques.

C. Contents of this Report

In this report the past work on electrical breakdown that is relevant to the handling of ultra-high power in waveguide systems is reviewed. Next, there is a discussion of the breakdown theory for non-uniform conditions and the use of the variational technique for obtaining solutions is developed. The purpose of the analysis is to account, more fully, for non-uniformities in the waveguide system. For a rough surface an expression is derived for the electric field which can be used in the breakdown theory. For a small foreign body located in the center of the waveguide an expression is derived for the temperature rise and an example is worked out. This report also includes an analysis of the cooling capability of gas flow inside the waveguide and is concluded with an analysis of a mode filter suitable for rectangular waveguide.

D. Review of Past Work

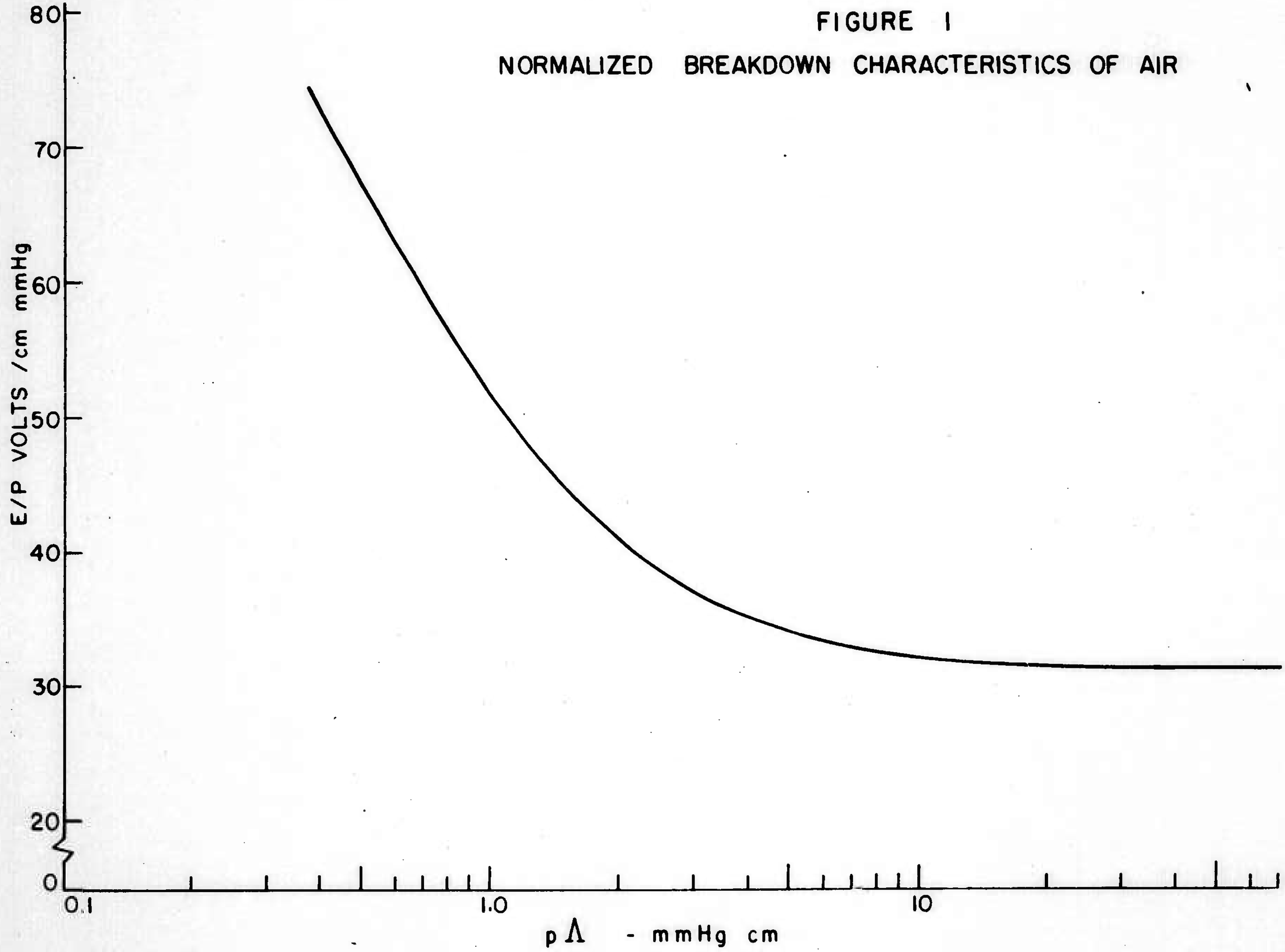
Study of microwave breakdown has been carried on at the Massachusetts Institute of Technology for a number of years.[1,2] An important result of this work has been the characterization of microwave breakdown by a useful normalization of parameters similar to that for dc breakdown. The normalized breakdown curve for air, a

plot of E/p versus pΛ, is shown in Figure 1 where p is the pressure, E is the effective electric field in volts per centimeter equivalent to a dc value that produces the same average ionization, and Λ is the diffusion length which depends upon the geometrical size of the breakdown region. The diffusion length may be generalized to describe nonuniform breakdown regions. Most of the experimental verification for the normalized breakdown curves comes from measurements made in waveguides and coaxial lines at pressures below one atmosphere.[1,2] Gases which have been explored extensively are air, nitrogen and some of the noble gases.

An important addition to the microwave breakdown theory was the inclusion of a correction for the modulation of the electron energy at the microwave frequency and the effect of pulse length.[3] The modulation occurring at the microwave frequency at pressures approximately above an atmosphere results in the breakdown threshold being reduced. This reduction is found because, at the peaks in the rf cycle, the mean electron energy actually exceeds that corresponding to the rms value of the electric field. For example, the common value of electric field for breakdown of air at one atmosphere under dc conditions is 30,000 volts per centimeter while the equivalent rms value of electric field at microwave frequencies is found to be 25,000 volts per centimeter. An application of the modified theory to waveguide systems including the effect of pulsed electromagnetic energy was carried out by Gould and summarized in his Handbook on Breakdown of Air in Waveguide Systems.[4] Most of the common air filled transmission lines

FIGURE I

NORMALIZED BREAKDOWN CHARACTERISTICS OF AIR



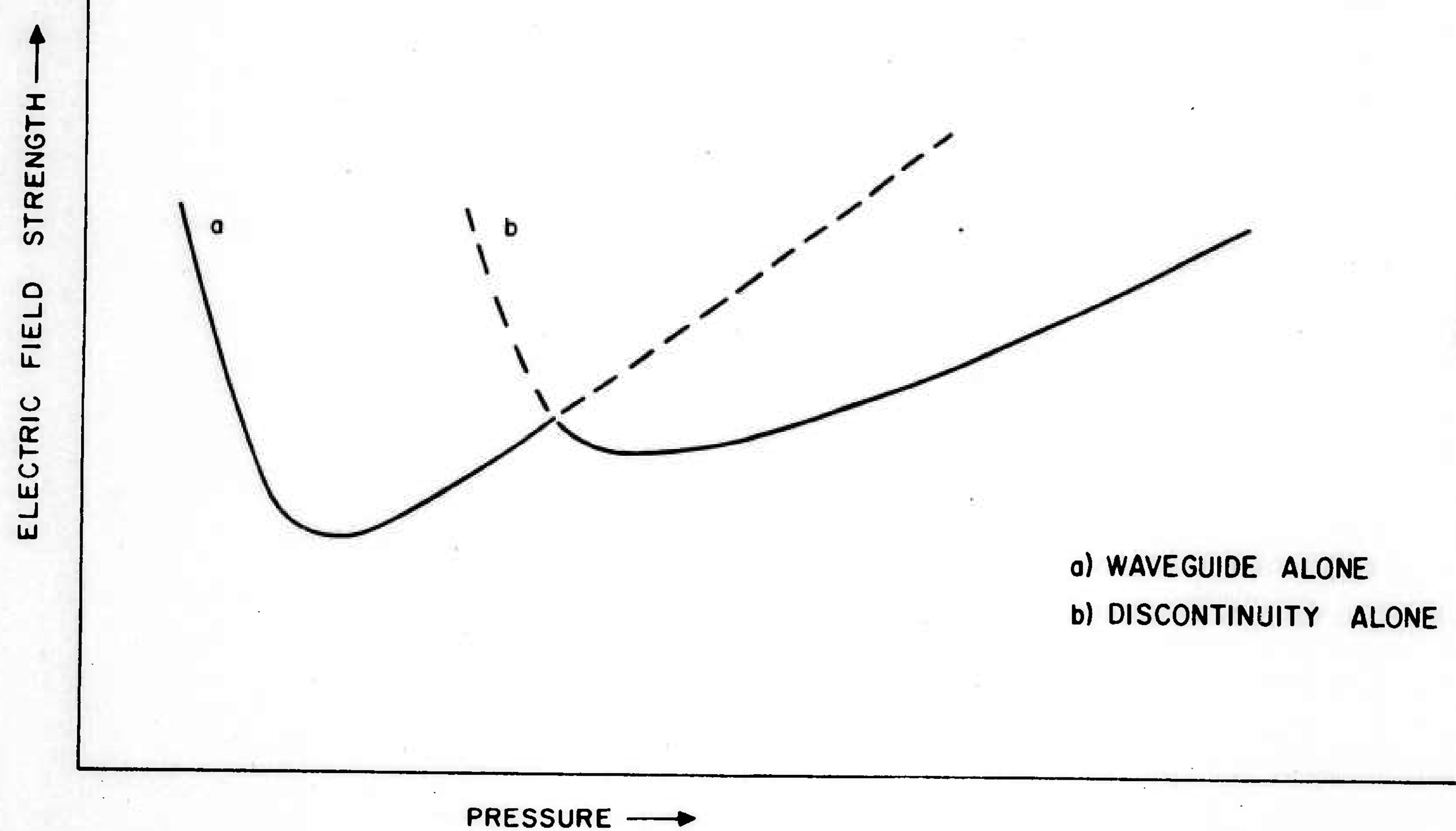
were covered in that Handbook.

Pertinent to the extension of waveguide systems to ultra-high powers is the use of high dielectric strength gases. Two gases that have come into common use are SF_6 and Freon 12. A number of experimenters have found that these two gases can give as much as a 10 to 1 improvement in the power handling capability,[5],[6] however, experience with high power systems has indicated that such improvements are not always possible to achieve. At Microwave Associates breakdown measurements have indicated that under uniform field conditions this improvement of 10 to 1 can indeed be achieved.[7]

An analysis of highly non-uniform electric fields and its effect on breakdown has been carried out for a small metallic hemisphere in an air filled waveguide cavity.[8] Based on this analysis it is possible to discuss in a general way the breakdown characteristics for similar small discontinuities. The effect of a discontinuity which produces a non-uniform electric field in a waveguide can be illustrated qualitatively by referring to Figure 2 where a typical breakdown characteristic of a transmission line and the breakdown characteristics of the discontinuity alone are shown. The complete curve for the discontinuity disregards the fact that a breakdown would occur elsewhere in the main volume of the waveguide for part of the pressure range. The values of field strength corresponds to that in the main region of the waveguide and the actual field strength at the discontinuity is larger than that in the main region of the waveguide. Each of the curves has a characteristic minimum breakdown field at

FIGURE 2

TYPICAL BREAKDOWN CHARACTERISTICS OF A WAVGUIDE WITH DISCONTINUITY



some critical pressure which is analogous to the minimum in the dc breakdown curves. The minimum field for the discontinuity occurs at the higher value of pressure because of the non-uniformity or highly-localized increase in the electric field. Since the region of electron production is highly localized, the electron diffusion out of that region is more rapid than it would be out of the main waveguide volume. Consequently the rise in electric field for breakdown begins sooner with decreasing pressure. Now, if the waveguide and the discontinuity are taken together, it is obvious that breakdown at a particular pressure will occur either in the waveguide or at the discontinuity depending upon which of the two has the lowest breakdown field strength. The composite breakdown characteristic is indicated by the solid curve in Figure 2. This effect is important because slight discontinuities in the waveguide that can be neglected under normal conditions can cause the break in the curve of Figure 2 to occur at pressures above an atmosphere. Thus the benefits of increasing pressure are lost in this range of pressures. Furthermore the properties of high dielectric strength gases are not known well enough to predict where these breaks will occur. What is lacking is a knowledge of the ionization and attachment coefficients.

Recently the temperature rise due to heating effects in waveguide under high average power conditions have become of practical importance. One analysis has concluded that for CW operation with standard waveguide the temperature will become excessive well before the rf power levels reach those at which breakdown can occur.[9] Of

course, the power limitations imposed by the waveguide temperature only represents the upper limit on the average power which can be handled by a waveguide system. It is clear that localized heating will further reduce the amount of average power which can be handled by a waveguide system. Small foreign bodies in the waveguide have been observed to cause such lowering of the breakdown power by more than an order of magnitude.[10]

Other recent work which is pertinent to this program is the effect of poor joints and the effect of surface roughness on waveguide breakdown.[11] Slightly offset joints were found to lower the breakdown power by as much as 50 percent The effect of surface roughness, with air at one atmosphere of pressure, was found to be negligible. This work was of a preliminary nature and indicates that further investigations are necessary to define the limitations imposed by poor joints and surface roughness. Another interesting observation has been the measurement of the movement of a microwave arc in an air filled waveguide under CW conditions where it was found that typical velocities were in the range from 1 to 20 feet per second.[10] Such measurements should include the effects of pulse width and pulse frequency, particularly for high dielectric strength gases.

Breakdown in waveguides that are highly evacuated are also of interest for ultra-high power because the absence of gas should prohibit the formation of any discharge. The greatest effort related to this subject has been concerned with the output sections of high power microwave tubes. There, the types of failures were connected with

electrons from the interaction region striking the waveguide windows, the deposition of material from the cathode on the window, gas bursts from the tube itself and finally multipactor discharge. The ultimate failure was in the destruction of the vacuum window of the tube. The most important of these mechanisms which should affect evacuated high power waveguides is the multipactor discharge or, as it is sometimes called, the resonant electron discharge.[2] This type of discharge results in the build-up of an electron cloud which travels back and forth between two surfaces in the evacuated region. The electron cloud travels in phase with the rf electric field and builds up its density by means of secondary emission each time the cloud strikes one of the metallic surfaces. In steady state operation secondary emission also serves to make up for those electrons which are lost from the oscillating cloud. Although the multipactor discharges are weak in comparison to arcs in a gas fill waveguide, the heating effect of the multipactor discharge can cause other serious problems that eventually lead to failure of the waveguide.

The problems of mode filters in over-sized waveguides have received attention for many years, but mainly in connection with the well-known TE_{01} mode of propagation in circular waveguide. The principle of the design is to provide good metallic paths for the currents of the desired mode while the currents in the undesired modes are forced to pass through lossy material or forced to couple to absorbing material external to the waveguide itself. An example of such a transmission line is a circular waveguide formed by a close wound

helix with lossy material external but adjacent to the helix.[12] Measurements on this circular waveguide indicated that the attenuation for the desired mode was only slightly larger than for a smooth pipe of the same dimensions. Although this method of obtaining mode filters is satisfactory for small wave lengths it does not appear to be entirely practical for greatly over-sized waveguide at frequencies of, say, 3000 megacycles. Therefore, it is worth considering over-sized rectangular waveguide since this allows the use of the well understood TE_{10} mode of transmission.

II. CONCLUSIONS

Based upon the analysis in Section III of this report the breakdown theory at microwave frequencies can be adapted to treat the additional non-uniformities resulting from gradients in gas density which in turn are caused by temperature gradients in the gas. It is also shown that the uniform field breakdown results are inadequate to allow comparison of breakdown strengths of various gases. This means that, in addition to breakdown studies under uniform conditions, experiments must also be done under controlled non-uniform conditions so that proper evaluation can be made. Further the non-uniformity in electric field at a rough surface was analyzed with a surface consisting of smooth hills and valleys. The expressions derived are suitable for use in the breakdown theory including non-uniform electric fields. The solution obtained led to field strengths at the peaks of the surface increased by 28% over the applied uniform field and heights of the peaks limited to approximately 10% of the spacing between the peaks. The analysis may be extended to account for greater increases in field strength at the surface due to surface roughness; however, the solutions become extremely complex and therefore were not carried further at this time.

The temperature rise of small foreign bodies in the waveguide that are cooled by radiation alone was analyzed. In a practical example it was found that the temperature can rise to a 1000°C in the vicinity of the small foreign body. Such an increase in temperature would correspond to a possible reduction in breakdown power of

10 to 1. This illustrates how seriously a small foreign body can effect the breakdown power in a waveguide.

Forced cooling of the waveguide by the flow of gas internal to the waveguide structure was analyzed. It was concluded that a factor of two increase in the power dissipation can be achieved under practical conditions. However, because of the rapid increase in gas temperature as it flows down the waveguide it becomes necessary to limit the flow of gas to a series of short lengths of pipe. For example, an X-band section might consist of a length 1.5 feet long while at S-band a suitable length might be as long as 6 feet.

Analysis of a mode filter in over-sized rectangular waveguide indicates that an acceptable difference in attenuation can be achieved between a fundamental mode, the TE_{10} mode, and all other modes which can propagate in the waveguide. The model analyzed for attenuation also suggests the form for a practical filter.

III. RECOMMENDATIONS

Because of the nature of the problems it becomes evident that experimental work should support the theoretical analysis on the effects of non-uniformities on breakdown. In addition experimental sections of mode filter should be built and tested to evaluate their effectiveness. In general, carrying out experimental work along side the theoretical work serves to guide the theoretical work into channels for obtaining the most effective solutions to the ultra-high power waveguide problems.

IV. DISCUSSION

A. Breakdown Theory for Non-Uniform Conditions

An analysis of breakdown begins with the diffusion equation which relates the rate of increase of electron density to the electron production and loss mechanisms. The production mechanism is ionization by electron impact and loss mechanisms are attachment to neutral molecules and diffusion out of the production region. The solution of the diffusion equation leads to a relationship between the electric field in the breakdown region, the pressure or density of the gas and the geometrical configuration. All solutions for a particular gas may be presented in the normalized form, a plot of the ratio E/p versus $p\Lambda$, shown earlier in Figure 2. The direct object in carrying through a particular solution of the diffusion equation is the characteristic diffusion length, Λ, which in general is also a function of E/p. Once the diffusion length is found the corresponding value of the high frequency ionization coefficient leads to the value of E/p for breakdown. A more detailed review of the theory is given below to introduce spacial non-uniformity in the gas density.

The diffusion equation is

$$\frac{dn}{dt} = (\nu_i - \nu_a)n - \nabla\vec{\Gamma} \tag{1}$$

On the left hand side of the equation is the rate of change of electron density as a function of time and on the right hand side are two familiar terms; first, the net rate of electron production due to ionizing and attaching collisions and, second, the net rate of electron loss due to gradients in the electron diffusion current density, $\vec{\Gamma} = n\vec{v}$. A non-zero value in the gradient in the electron diffusion current can arise from a gradient of electron density alone. For example, non-uniform rates of electron production in the volume would lead to this effect. Secondly, a gradient in the diffusion current can arise when there is a spatial variation in the mean electron energy arising, for example, from a non-uniform electric field. Thirdly, a gradient in the diffusion current can arise from a gradient in the density of the molecules which, because of the spatial variation of electron collisions, also leads to non-uniformities in electron production and mean energy.

In order to introduce the non-uniformities into the diffusion equation it is necessary to find an appropriate expression for the electron diffusion current, the product of electron density and velocity. A simplified model for obtaining the essential features of the electron transport is shown in Figure 3. In order to count all the electrons which diffuse through the small surface dA, per unit time, all the electrons which reach the surface dA, after having made just one collision in the differential volume $d\tau$ are added together. More specifically the electrons which have just made a collision in the differential volume $d\tau$ in time dt are determined; but, only those

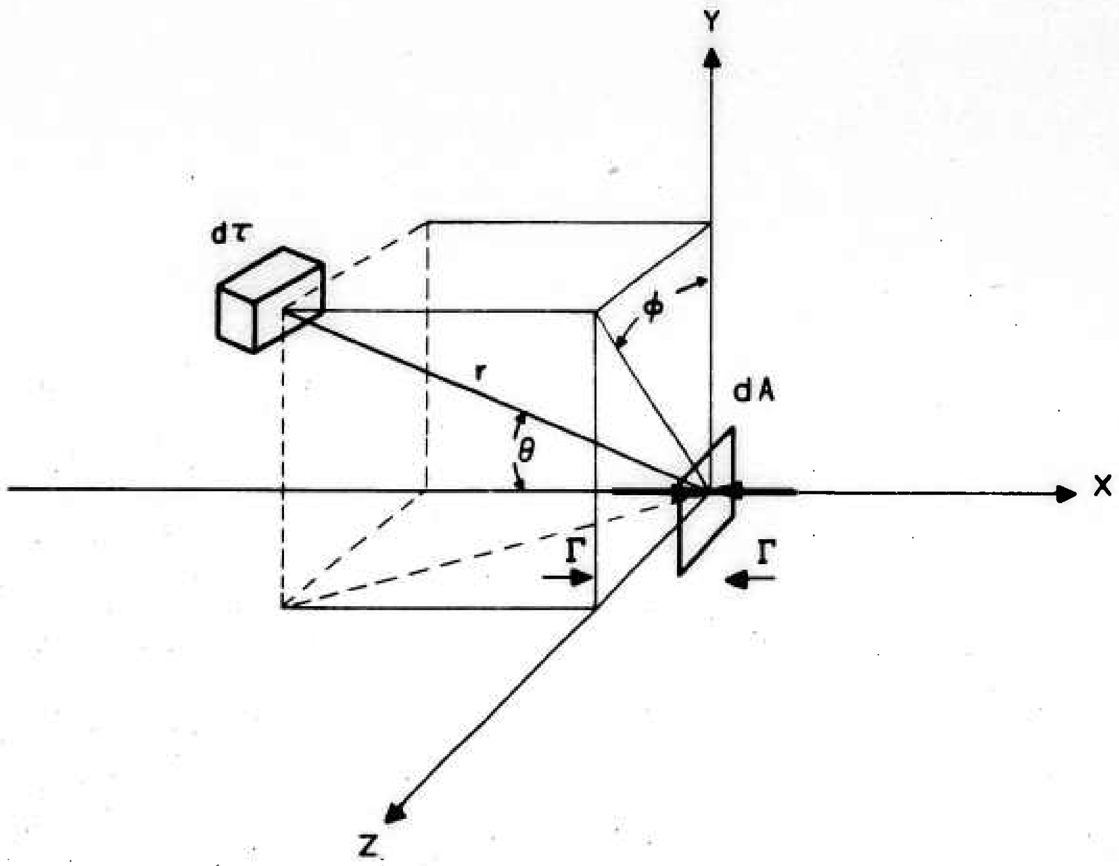


FIGURE 3
MODEL USED FOR DERIVING EFFECTS
OF NONUNIFORMITIES

electrons which survive, without further collisions to pass through the cross-sectional area dA, are counted. The net flow of electrons through the surface is then found by obtaining the integrated effect of the entire volume to give the diffusion current density.

The differential diffusion current flowing to the right is given by the expression:

$$d\Gamma = \frac{1}{4\pi} \nu n e^{-r/\lambda} \sin\theta \cos\theta \, d\theta \, d\phi \, dr \, . \qquad (2)$$

This analysis follows the notation and the derivation given by Sears.[13] Aside from the various factors which enter because of geometrical considerations, there are three important quantities which are evaluated at the elemental volume $d\tau$: the electron collision frequency (ν), the electron density (n), and the exponential factor containing the mean free path (λ) representing the fraction of electrons which survive without collision in reaching the surface area dA. With the introduction of gradients in the x direction for the electron density, the electron collision frequency and the electron mean free path, the above quantities may be approximated to first order by the expressions:

$$n = n_o - r \cos\theta \frac{dn}{dx} \, , \qquad (3)$$

$$\nu = \nu_o - r\cos\theta\,\frac{d\nu}{dx}\,, \tag{4}$$

$$e^{-r/\lambda} = \left(1 - \frac{r}{\lambda_o^2}\,r\cos\theta\,\frac{d\lambda}{dx}\right) e^{-r/\lambda_o} \tag{5}$$

where $r\cos\theta = \Delta x$ is a small quantity.

The substitution of Equations (3), (4), and (5) into Equation (2) for the component of the diffusion current to the right and retaining only the first order terms in $r\cos\theta$ yields:

$$\underset{\rightarrow}{d\Gamma} = \frac{1}{4\pi}\left[n_o\nu_o - \frac{d(\nu n)}{dx}\,r\cos\theta - \frac{n_o\nu_o}{\lambda_o^2}\,\frac{d\lambda}{dx}\,r^2\cos\theta\right] e^{-r/\lambda_o} \tag{6}$$

A similar term may be derived for the differential diffusion current to the left. The incremental terms are then of opposite sign. When both expressions are intergrated and then added the resulting expression is

$$\Gamma = \Gamma_{\rightarrow} - \Gamma_{\leftarrow} = -\frac{d}{dx}\left(\frac{\nu\lambda_o^2}{3} n\right) - 2\,\frac{\nu_o\lambda_o^2}{3}\, n_o\, \frac{d(\lambda/\lambda_o)}{dx} \tag{7}$$

The first term on the right hand side of Equation (7) gives the combined effect of a gradient in the electron collision frequency and the electron density. The second term in Equation (7) gives the effect of a gradient in the mean free path.

The diffusion equation for analyzing breakdown is obtained by introducing the standard definition for diffusion coefficient which is

$$D = \frac{\nu\lambda_o^2}{3} = \frac{\bar{v}\lambda_o}{3}\,, \tag{8}$$

where $\bar{v} = \nu\lambda_o$ is the mean velocity of the electrons.

Equation (7) may then be put into the following form

$$\Gamma = -\frac{d}{dx}(Dn) - 2D_o n_o \frac{d(\lambda/\lambda_o)}{dx} \tag{9}$$

By extension of Equation (9) (which only applies to gradients in the x direction,) a more general expression, can be written as

$$\Gamma = -\nabla(Dn) - 2Dn\nabla\ (\lambda/\lambda_o). \tag{10}$$

Finally a new variable ψ is defined

$$\psi = Dn \tag{11}$$

This variable is substituted into Equation (10) and the result in turn is substituted into Equation (1), to give a partial differential equation for ψ:

$$\frac{1}{D}\frac{d\psi}{dt} = \xi\ E^2\psi + \nabla^2\psi + \nabla\cdot\ \left[2\psi\nabla(\lambda/\lambda_o)\right] \tag{12}$$

where

$$\xi = \frac{\nu_i - \nu_a}{DE^2} \tag{13}$$

is the high frequency ionization coefficient. It is seen that the right hand side of Equation (12) contains three terms, the first two of which are recognized as those which are usually included in the breakdown theory. The third term is due to the non-uniformity in mean-free-path or gas density. This last term involving the gradient in the mean free path of the electrons adds to the complexity of solving the diffusion equation.

Approximate solutions for the breakdown condition under CW operation may be found by setting the left hand side of Equation (12) equal to zero and by further assuming that the third term on the right of Equation (12) may be neglected. This last assumption does not eliminate completely the effect of variations in λ as spatial variations of gas density still remain in the coefficient of the first term by virtue of the ionization frequency, attachment frequency and diffusion coefficient. The effect of neglecting this term results in the loss of electrons by the diffusion from the breakdown region to be smaller than is actually the case. Consequently neglecting the third term in Equation (12) yields values for breakdown power which are lower than the true value. Since, for our purposes, the gradient in gas density will arise from a gradient in gas temperature, this gradient in density can be taken into account by defining an effective pressure, p_e, in terms of the ambient pressure, p_o, and a temperature ratio:

$$p_e = p_o\, T_o / T \; . \tag{14a}$$

and for the mean free path

$$\lambda_e = \lambda_o\, T / T_o \; , \tag{14b}$$

where T_o is the ambient temperature. The diffusion equation to be solved, as simplified from Equation (12), is then

$$\frac{\Delta^2 \psi}{\psi} + p_e^2\, \xi \left(\frac{E^2}{p_e^2} \right) = 0 \; . \tag{15}$$

One method for solving the diffusion equation, Equation (15), for the function ψ, since it is generally difficult to find an exact solution, is to use the variational approach. This approach consists of assuming trial functions for ψ with variational parameters and then finding the best value of the parameter suiting the boundary condition. In order to do this Equation (15) is modified to the

following form

$$\frac{\nabla^2\psi}{\psi} + p_e'^2\,\xi'\,X'^2 \left(\frac{p_e}{p_e'}\right)^2 \left(\frac{\xi}{\xi'}\right)\left(\frac{X}{X'}\right)^2 = 0 \qquad (16)$$

where the prime d quantities are the values of the variables at some reference point in the breakdown region and $X = E/p_e$. Next, application of the variational principle requires that the ratio of the following integrals be a minimum,

$$k^2 = \int(\nabla\psi)^2\,dV \Big/ \int\psi^2 \left(\frac{p_e}{p}\right)^2 \left(\frac{\xi}{\xi'}\right)\left(\frac{X}{X'}\right)^2 dV \qquad (17)$$

The minimum value is then taken to be equal to the product $p_e'^2\xi'X'^2 = k^2$ min., the constant coefficient separated out in Equation (16). The evaluation of the right hand side of Equation (17) involves the spatial distributions of the normalized pressure, the high frequency ionization coefficient, and the electric field. Note that the electric field strength is included in the variable X, the ratio of E divided by p_e. The breakdown field strength for the particular geometric configuration and gas is found from that value of the high frequency ionization coefficient which satisfied the relationship,

$$\xi'^2 X'^2 = \frac{1}{p_e'^2 \Lambda^2} \tag{18}$$

where the term Λ, the diffusion length, is introducted as the reciprocal of k min. in Equation (17). Consideration of the manner in which the solution for ψ and the corresponding diffusion length are obtained indicates that the spatial variations of all three quantities are important, especially the rapid spatial variation of the high frequency ionization coefficient which also depends upon the nature of the gas. Thus, under non-uniform conditions, comparison of the breakdown strength between various gases may not be definitive.

B. <u>The Electric Field at a Rough Surface</u>

As part of the problem of solving for the breakdown threshold under non-uniform field conditions, the spatial variation of the electric field is required. For this purpose an analysis was made of the electric field at a rough surface in a waveguide where the field is of maximum value. To make the solution tractable the rough surface is first replaced by a uniformly varying surface which satisfies Laplaces equation. Solutions of Laplaces equation are justified for rough surfaces where the spacing is small compared to a wavelength. A sketch of the lowest order solution for the surface is given in Figure 4. There the various dimensions and the coordinate system are defined. The lowest order solution is given by the following expressions for potential and electric field perpendicular to the plane of

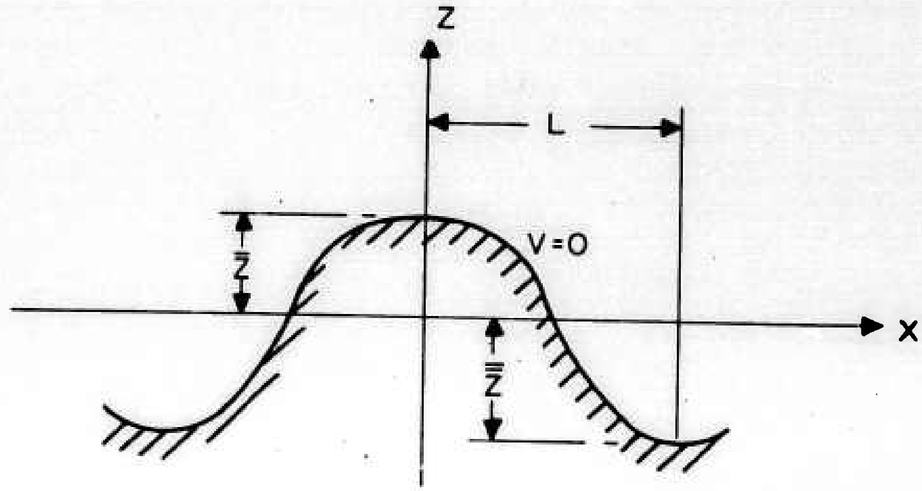
the surface:

$$V = -E_o \left[z - \bar{z}\, e^{-\frac{\sqrt{2}\pi}{L}(z - \bar{z})} \cos \frac{\pi}{L} x \cos \frac{\pi}{L} y \right] \tag{19}$$

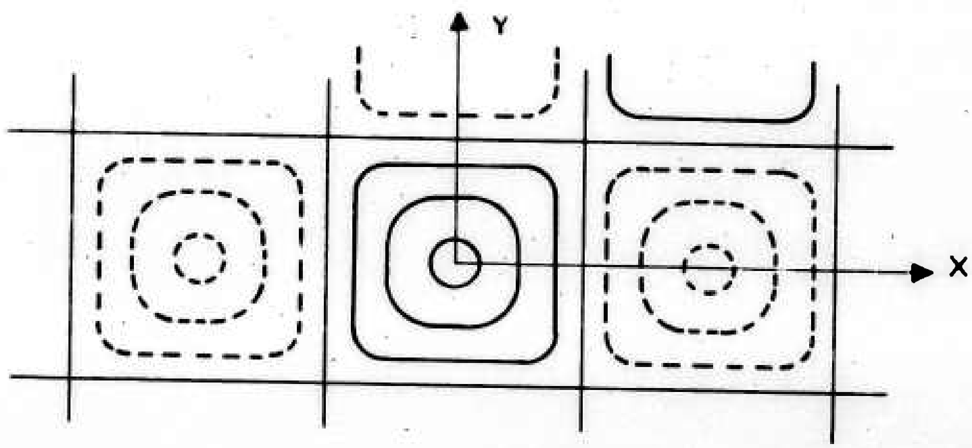
$$E_z = E_o \left[1 + \frac{2\pi}{L}\, e^{-\frac{\sqrt{2}\pi}{L}(z - \bar{z})} \cos \frac{\pi}{L} x \cos \frac{\pi}{L} y \right] \tag{20}$$

The form of the solution is sketched in Figures 4a and 4b. A section through one of the peaks of the surface is shown relative to the reference plane in Figure 4a. The height above the plane, designated by $\bar{z}$, is generally different than the depth of the valley, designated by $\bar{\bar{z}}$. The solution is chosen so that the potential is zero at the top of the peak for $z = \bar{z}$. Therefore the surface shown corresponds to a zero potential surface which may conveniently be choosen to represent the rough surface. The expression given in Equation (20) for the z component of the electric field shows that as z increases the effect of the surface roughness vanishes within a distance equal to the spacing between the peaks, 2L. A top view of the surface is sketched in Figure 4b to show that a section at the reference plane is square while at the peak and valley the sections approach circular shapes. Since this is a solution of Laplaces equation the result applies to waveguides in which $L \ll \lambda g$.

The expression given in Equation (19) defines the rough surface



a.) CROSS SECTION OF SURFACE



b.) TOP VIEW OF SURFACE

FIGURE 4
MODEL OF A ROUGH SURFACE

as well as the adjacent equipotential surfaces, zero potential defining the actual rough surface. Careful examination of the solution indicates that only a mild surface roughness can be thus represented. This becomes apparent in relating the height of the peak to the depth of the valley, $\bar{z}$ and $\bar{\bar{z}}$ respectively. In Equation (19) taking V equal to zero and the value of z corresponding to the valley, $z = -\bar{\bar{z}}$, a relationship between $\bar{z}$ and $\bar{\bar{z}}$ is obtained,

$$\frac{\sqrt{2}\pi}{L}\bar{\bar{z}}\, e^{-\frac{\sqrt{2}\pi}{L}\bar{\bar{z}}} = \frac{\sqrt{2}\pi}{L}\bar{z} e^{\frac{\sqrt{2}\pi}{L}\bar{z}} . \qquad (21)$$

It can be seen in Equation (21) that for valid solutions there is a maximum value of the left hand side for $\bar{\bar{z}} = L/\sqrt{2}\pi$. For this value of $\bar{\bar{z}}$ Equation (21) gives a transcendental expression for $\bar{z}$ which may be solved graphically, $\bar{z} = .28L/\sqrt{2}\pi$. The significance of this result is that the electric field, at most, is increased above the original uniform electric field by only 28%. Furthermore the maximum value of $\bar{z}$ is only a small fraction of the value 2L, the spacing between two adjacent peaks. For completeness the x and y components of electric field in the vicinity of the peaks are now given

$$E_x = E_o \frac{\pi \bar{z}}{L} e^{-\frac{\sqrt{2}\pi}{L}(z - \bar{z})} \sin \frac{\pi x}{L} \cos \frac{\pi y}{L} \quad (22)$$

$$E_y = E_o \frac{\pi \bar{z}}{L} e^{-\frac{\sqrt{2}\pi}{L}(z - \bar{z})} \cos \frac{\pi x}{L} \sin \frac{\pi y}{L} . \quad (23)$$

The purpose for carrying through this solution was to obtain an expression for the electric field for use in the diffusion equation for breakdown and also to obtain some estimate of the field strengths near a uniformly rough surface in a waveguide. The lowest order solution was found to yield maximum field strengths only 28 percent higher than the applied uniform field. Inclusion of higher order solutions would permit larger increases in field strength. Because the high field region was found to be highly localized, $\bar{z} << L$, it would be unlikely that the breakdown would be governed by the field strength immediately adjacent to the surface. In other words electron diffusion, except at very high pressures, would limit the build-up of an electron density near the rough surface so that breakdown will not be reduced by the full amount indicated by the peak values of electric field.

C. Waveguide Cooling by an Internal Coolant

The effect of temperature rise in waveguide or near a excessively hot portion of a waveguide results in a reduction in the gas density

with a corresponding reduction in the breakdown power of the entire system.[4] An analysis of waveguide temperature as a function of line power or of power dissipated per unit length has been carried elsewhere.[9,14] Some pertinent results of temperature rise for standard x-band and s-band waveguides are reproduced in Figures 5 and 6.[14] Figure 5 gives the temperature for power dissipated per foot and Figure 6 for average line power. These are representative of natural cooling with black outer surfaces. The purpose of the following analysis is to examine another means for cooling waveguide systems.

An attractive means for cooling a waveguide would be to flow a coolant inside the waveguide. Since a waveguide system may be considered as a network of pipes, it would seem practical to utilize it also to carry a coolant. The coolant would have to provide low r.f. losses and have a high dielectric strength. In this analysis the heat carried away by a particular flow of gas, the coolant, is calculated and the waveguide temperature under such a cooling action is calculated. The temperatures of the waveguide walls are important because they have an effect on the breakdown of the waveguide even though the bulk of the gas is at a lower temperature.

The analysis involves the two heat transfer equations,[15]

$$q = h(\Delta t)_L CL \tag{24}$$

FIGURE 5
WAVEGUIDE TEMPERATURE RISE AS A FUNCTION OF POWER DISSIPATION

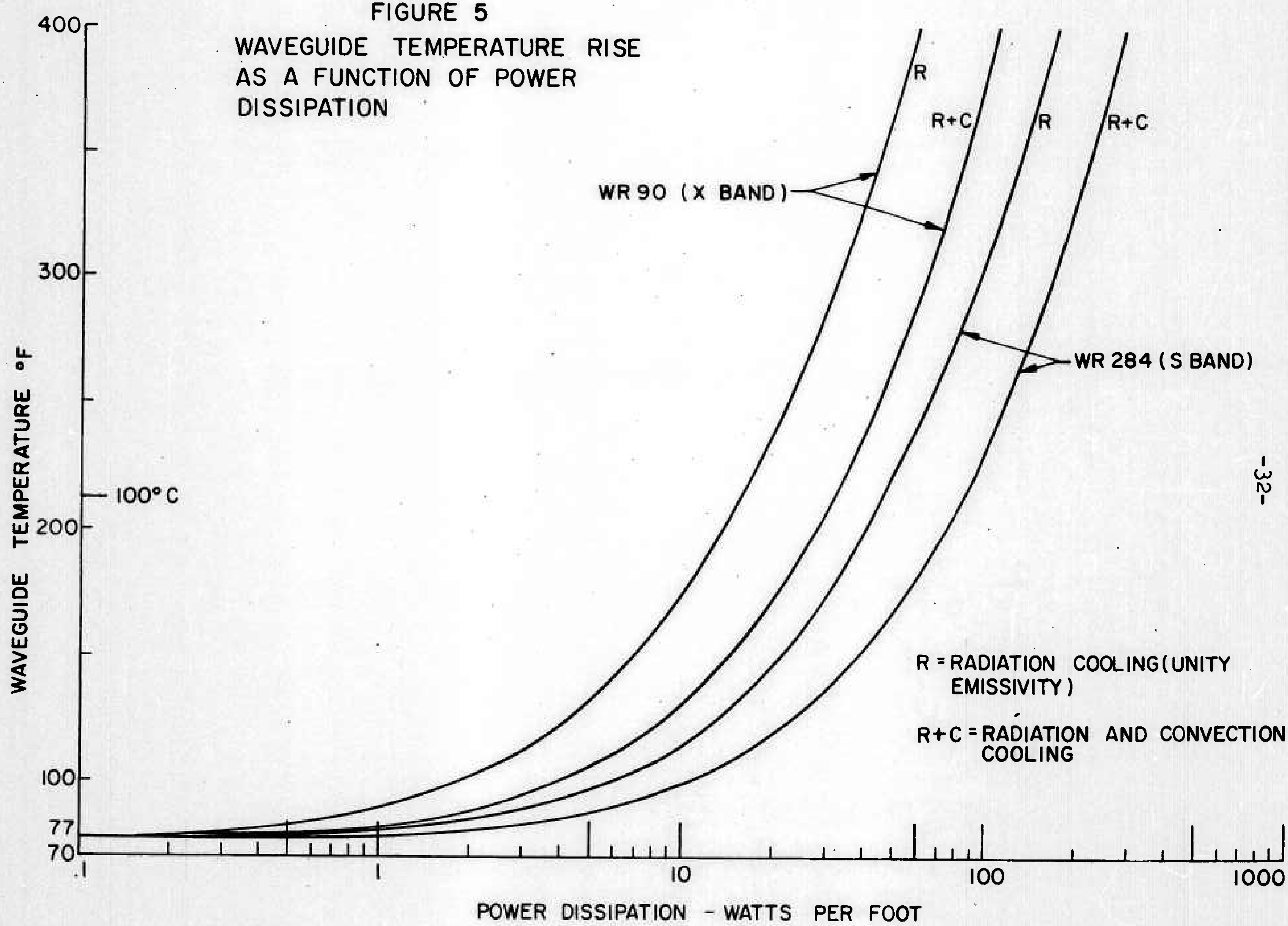
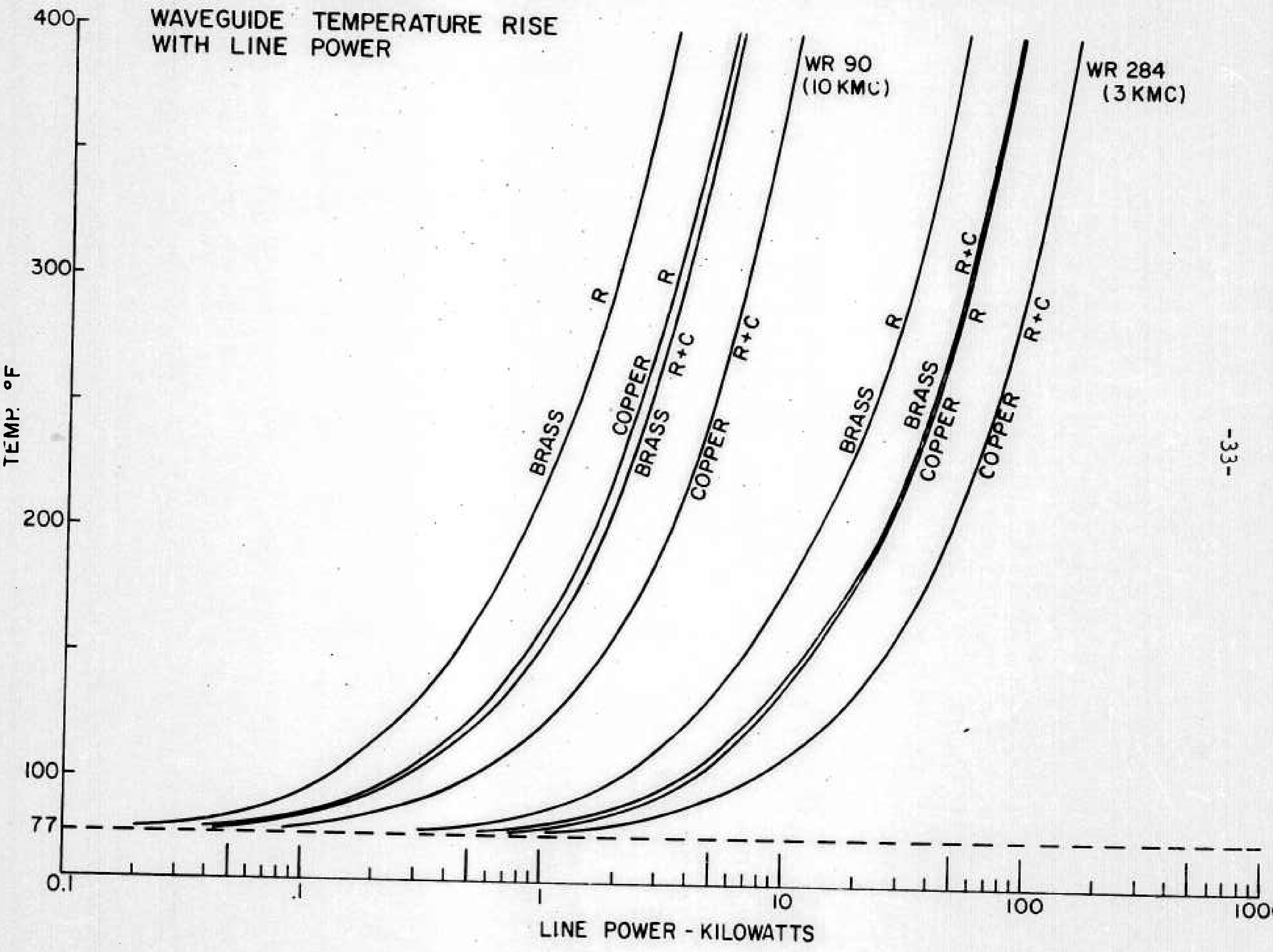


FIGURE 6

WAVEGUIDE TEMPERATURE RISE WITH LINE POWER



$$q = c_p G(t_2 - t_1) AL \ . \qquad (25)$$

Equation (24) gives the rate of heat transfer from the walls of the pipe to the gas flowing within and Equation (25) gives the total rate of heat transfer to the gas in terms of the heat capacity of the gas. Equation (25), does not involve the temperature of the waveguide walls. The geometric quantities are specified in Figures 7 and 8 and the coefficient of heat transfer, h, is given by

$$h = 0.0144 \ c_p G^{0.8} \ (D^{0.2}) \qquad (26)$$

There c_p is the specific heat of the gas, G is the mass flow, and D is an effective diameter for the pipe equal to 4 A/C. The quantity $(\Delta t)_L$ of Equation (24), the logarithmic change in temperature, is defined as follows

$$(\Delta t)_L = \frac{t_2 - t_1}{\ln\dfrac{t_w - t_1}{t_w - t_2}} \cong \frac{\Delta t}{1 + \dfrac{\delta t}{2\Delta t}} \qquad (27)$$

This expression includes an approximation in terms of the rise in gas temperature from input to output and the difference in temperature between the input gas and the waveguide wall. These quantities are indicated by $\Delta t = t_2 - t_1$ and $\delta t = t_w - t_1$ respectively. Calculations have indicated that this approximate expression is good for 10% accuracy up to a value of $\frac{\delta t}{\Delta t}$ of 0.5. With the aid of Equations (24) through (27), making appropriate conversions of units and introducing several new quantities, an expression can be derived for the power carried away per unit length by gas flow inside the pipe;

$$\frac{Pd}{L} = 0.35\, c_p (J\rho)^{0.8} \frac{(a+b)^{1.2}}{ab} \Delta t\left[\sqrt{\frac{1}{Y^2} + \frac{2}{Y}} - 1\right] \qquad (28)$$

The quantity J represents the flow of gas in cubic feet per minute, the quantity ρ represents the gas density in pounds per cubic feet, the quantities a and b are the width and height of the waveguide in

feet and Δt is the difference in temperature between the waveguide wall and the input gas expressed in degrees centigrade. The power is expressed in watts and the length in feet. The quantity Y in Equation (28) is given by the expression:

$$Y = 1.1 \times 10^{-2} \frac{L}{(J\rho)^{0.2}} \frac{(a + b)^{1.2}}{a\ b} \tag{29}$$

Although it is not immediately apparent, for small values of Y in Equation (28), the term in brackets containing Y becomes unity. The significance of small values of Y is that it corresponds to large flow rates of gas which result in small gas temperature rises, or conversely it corresponds to short lengths of pipe. For a waveguide cooling system the parameters should be adjusted so that Y is small, since this would give the most effective cooling of the waveguide system and result in the most uniform temperature distribution.

Examples of the effectiveness of this method of cooling waveguides are illustrated by computations for standard x-band and s-band waveguide for air at a pressure of one atmosphere at the input. The computations are plotted in Figures 7 and 8. For an air flow corresponding to ten miles an hour, s-band waveguide can dissipate a hundred watts per foot along a section of waveguide six feet long. Correspondingly larger amounts of power could be dissipated at higher

FIGURE 7

POWER DISSIPATION BY INTERNAL FLOW OF GAS, X-BAND

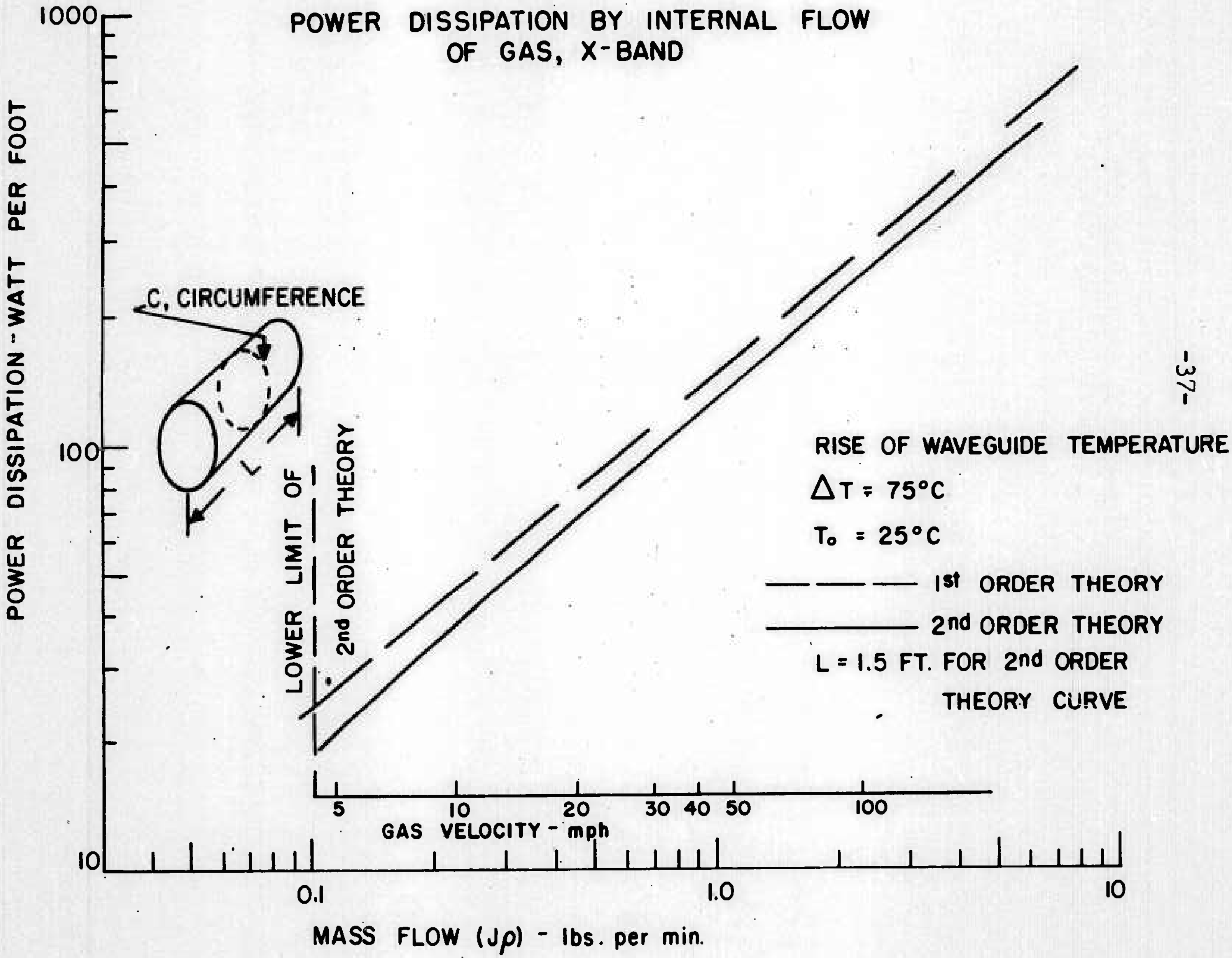
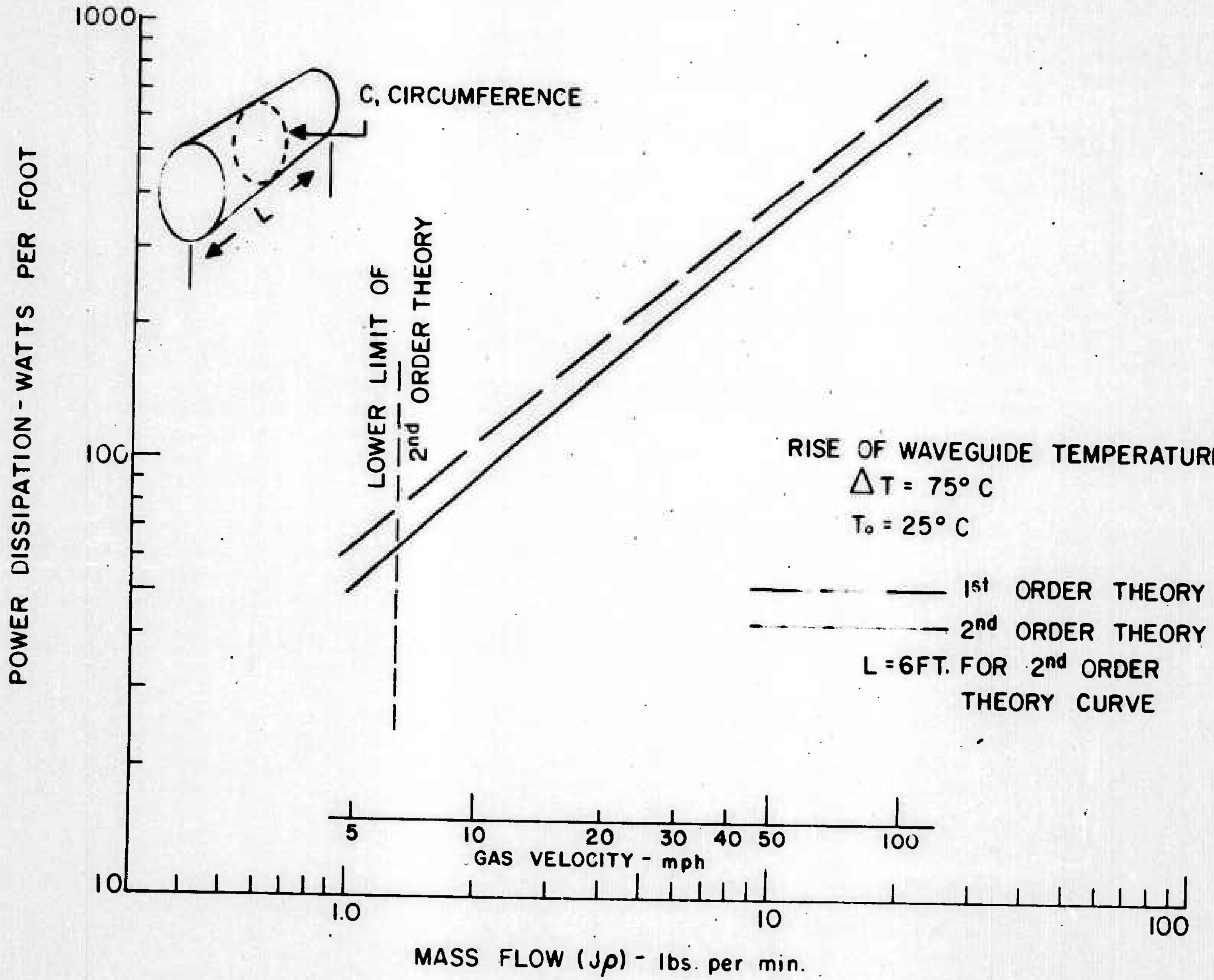


FIGURE 8

POWER DISSIPATION BY INTERNAL FLOW OF GAS, S-BAND



velocities or by utilizing a heavier gas and/or increasing the gas pressure at the input. In any event there is some question as to what a practical value of velocity should be at the input end of the waveguide. In a section of x-band waveguide which is 1.5 feet long an air velocity of approximately 30 miles per hour is required to carry away a hundred watts per foot, while at a velocity of ten miles an hour about forty watts per foot could be carried away. Both of these calculations were based on a waveguide wall temperature of seventy-five degrees centigrade. Comparing these values with those for ordinary convection and radiation cooling from the outer surfaces of the waveguide (see Figures 5 and 6) it would be practical to, at least, double the amount of power dissipation by a forced air flow through the inside of the waveguide. If more rapid circulation of gases through the waveguide can be achieved in closed pressurized systems, then correspondingly greater power dissipation could be handled in the waveguide system.

The greatest limitation of forced internal cooling appears to be that long lengths of waveguide systems, (say a hundred feet) can not be cooled by simply injecting air at one end of the system and then removing the heated air from the other end of the system. It appears that it is necessary to divide the system up into several shorter sections which can be cooled independently by gas flow to a heat exchanger. The need for a heat exchanger is evident because the most effective gas-circulating system is closed so that elevated pressures and gases other than air can be used. At the same time the

breakdown threshold of the waveguide would be raised.

This type of cooling the waveguide gives rise to another interesting aspect of breakdown under non-uniform conditions, since the region at the hot walls is more susceptible to breakdown. However, because of the rapid drop in the gas temperature away from the walls resulting from the air flow, a non-uniformity in gas density exists. This non-uniformity counteracts the reduction in the power handling capabilities in that a more rapid diffusion of electrons from the hot regions occurs. As discussed in Section IV A the temperature gradient across the waveguide can be taken into account in the diffusion equation used for calculating the breakdown power.

D. Reduction in the Breakdown Threshold by Small Foreign Particles

The presence of small particles of foreign matter in a waveguide system leads to a reduction in the power handling capability as a result of the particle becoming heated. This local elevation in gas temperature lowers the field strength for breakdown in the immediate vicinity. This effect is in addition to any localized increase in field strength due to distortion in the electric field strength. Such effects have already been observed in high average power systems and so it would seem worthwhile to analyze this problem in some detail. The case of a small particle suspended in the center of a waveguide is treated. It is assumed that its dielectric constant and conductivity are such that there is an unimportant change in the local electric field. It is further assumed that the particle is cooled only by radiation. This is reasonable since convection cooling

is not expected to be effective. The power absorbed by the particle is given by

$$P_{ave} \cong \left(\frac{4}{3}\pi\ R^3\right)\ \omega\varepsilon\ \tan\delta\ E^2\ , \tag{30}$$

where R is the radius of the particle, ω is the angular frequency, $\tan\delta$ is the loss factor, and E is the electric field. The power carried away by radiation is given by

$$P_{ave} = e\sigma'\ (t^4 - t_o{}^4)\ 4\pi R^2\ , \tag{31}$$

where e is the emissivity, σ' the Stephan-Boltzmann constant, t is the absolute temperatue, and t_o is the absolute ambient temperature. Equating Equations (30) and (31) an expression for the temperature is obtained

$$t^4 = t_o{}^4 + RE^2\omega\varepsilon\ \tan\ \delta/3e\sigma'\ . \tag{32}$$

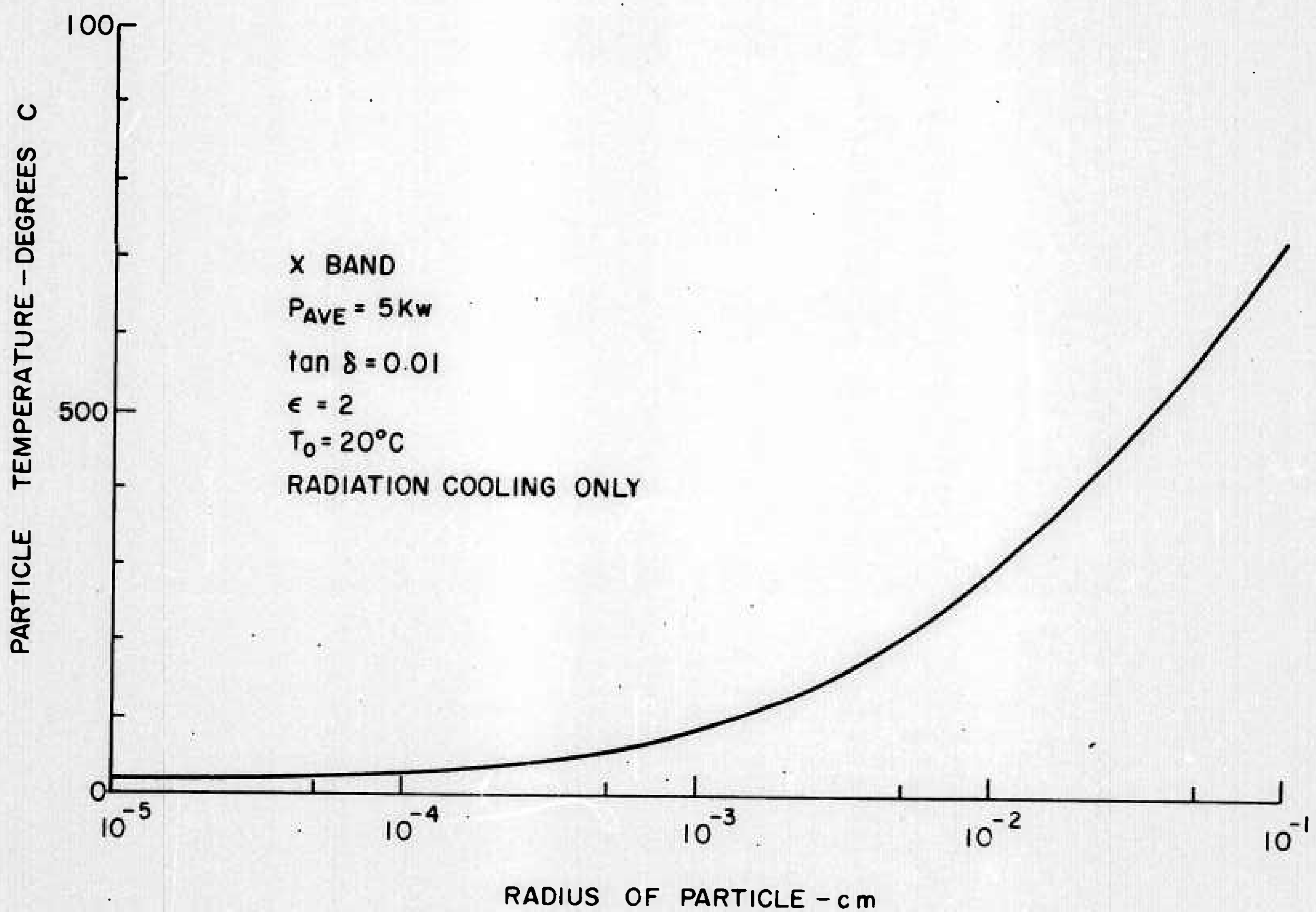
The expression shows that, as the radius of the particle is increased, the temperature also increases. The temperature increases, as expected, with the square of the electric field, the loss tangent, and the dielectric constant. Power carried by the waveguide may now be introduced into the expression and some of the constants evaluated to yield

$$t^4 = t_o^4 + \frac{R\omega\epsilon \tan \delta \, P}{3.99 \times 10^{-3} \sigma \, ab\lambda/\lambda g} \tag{33}$$

An example of the temperature rise of a small foreign particle in a waveguide was computed and the results are plotted in Figure 9. The temperature of the foreign particle is shown as a function of its size where the particle is situated in x-band waveguide carrying an average power of five kilowatts. The value of the loss tangent was assumed to be only .01, the ambient temperature 20°C and the dielectric constant 2. It is startling to see that for a particle radius of a tenth of a centimeter, the temperature would be about 730°C. Such a localized temperature rise is sufficient to lower the breakdown power by a factor of about five. This estimate is based on the assumption that the breakdown field strength is reduced in proportion to the square of the temperature ratio. A more complete analysis would include the effect of the gradient in the density of the gas molecules on electron diffusion.

FIGURE 9

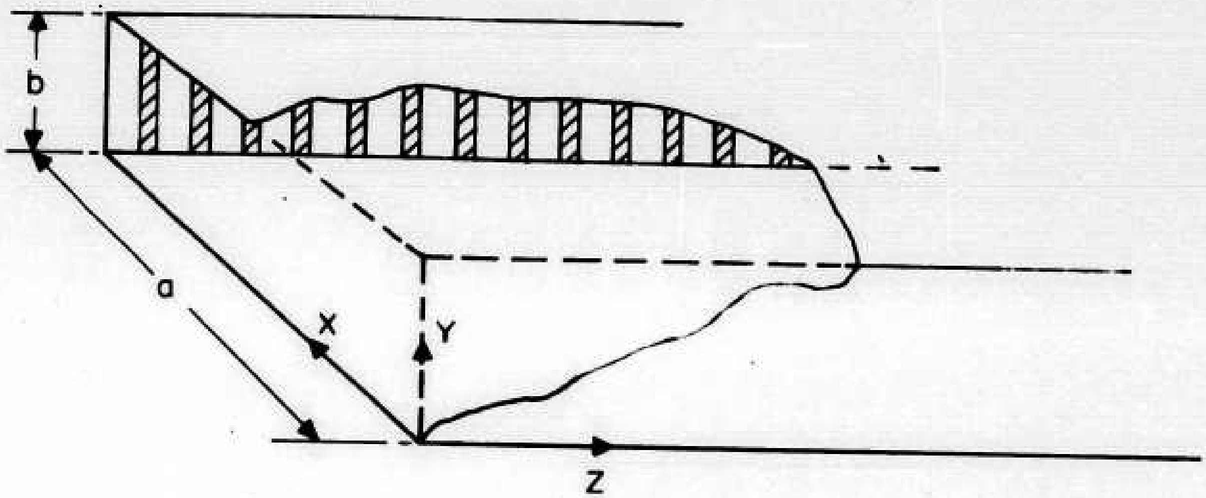
TEMPERATURE OF FOREIGN PARTICLE IN A WAVEGUIDE



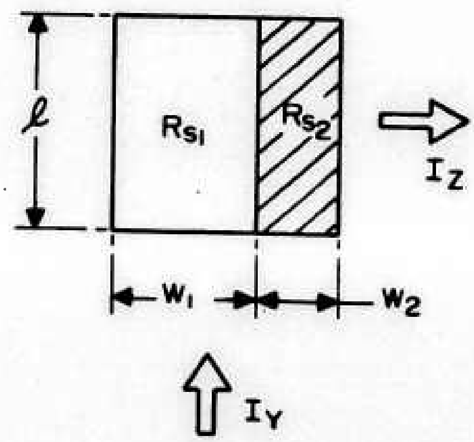
E. Unwanted-Mode Filtering in Over-Sized Waveguides

The general principles used for filtering or suppressing unwanted modes in over-sized waveguide does not change over the range of frequencies of interest in this program. The object is to interrupt the current flow of the unwanted modes while not interferring with the current flow of the desired mode of propagation. However, in application of this general principle to waveguide sizes which range from a quarter of an inch up to six inches considerable difference in construction is possible and even necessary. For example, a close wound helical structure for TE_{01} waveguide[13] is completely suitable for very small wave lengths but unsuitable for large wave length waveguide. Mode filters consisting of vanes projecting into the waveguide or other types of insertions are not particularly desirable as they increase the power absorbed in that part of the system and themselves become heated to the extent of reducing the breakdown power of the system. Localized increase in electric field strength also reduces the breakdown threshold. In this report a mode filter for rectangular waveguide carrying the TE_{10} mode is analyzed.

A possible mode filter of modified waveguide may be constructed with side walls consisting of alternate strips of good and poor conducting materials. A sketch of the filter is shown in Figure 10. The poor-conducting medium is selected so that it is relatively poor with respect to such metals as copper or aluminum but it is still electrically a conductor at micfowave frequencies. The strips are



a.) CUT AWAY SECTION OF FILTER



b.) TYPICAL ELEMENT OF ANISOTROPIC SURFACE

FIGURE 10
MODE SUPPRESSION FILTER IN RECTANGULAR WAVEGUIDE

narrow compared to a wave length so that the concept of an equivalent surface resistivity can be employed. There will be one value of surface resistance in the direction parallel to the strips and another value perpendicular to the strips. Since the walls are still conductors, the field quantities are not significantly altered so that the usual approach for computing waveguide attenuation may be used.

Expressions for the equivalent surface resistances for the side walls of the waveguide may be derived for the directions parallel and perpendicular to the narrow strips. A typical section of the side wall of height ℓ consisting of a pair of strips respectively of surface resistance R_{s1} and width w_1 and of surface resistance R_{s2} and width w_2 is shown in Figure 10b. Consideration of the way in which series and parallel resistances combine lead to the following expression for the parallel, y direction, and perpendicular, z direction, surface resistances:

$$R_{sy} = (w_1 + w_2) \frac{R_{s1}R_{s2}}{w_1R_{s2} + w_2R_{s1}} \tag{34}$$

$$R_{sZ} = \frac{1}{w_1 + w_2} (w_1R_{s1} + w_2R_{s2}) \tag{35}$$

In order to derive expressions for attenuation of the various modes of propagation it will be necessary to evaluate a loss integral for a unit length of transmission line. For rectangular waveguide this integral consists of two parts;

$$P_d = \frac{1}{2}\int \bar{E}\cdot\bar{I}_s \, d\ell = \int_0^a R_s\left[I_x^2 + I_y^2\right] dx + \int_0^b \left[R_{sy}I_y^2 + R_{sZ}I_Z^2\right] dy \qquad (36)$$

In accordance with the assumption that the field quantities are essentially identical to those in the lossless case, the spacial variation of the surface currents are well known and evaluation of the integrals in Equation (36) follows in a straight-forward manner. The attenuation for the various modes is finally obtained from

$$\alpha = \frac{1}{2} P_d / P_o \qquad (37)$$

where P_o is the transmitted line power.

The derived expressions for attenuation for various modes are shown in Table I where the anisotropic case is compared to the convention isotropic case. The significant result is that the attenuation for the TE_{m0} modes involve the surface resistivity of the poor

MODES	α WITH ANISOTROPIC WALLS	α WITH ISOTROPIC WALLS
TE_{m0}	$\frac{1}{b}\frac{R_s}{R_o}\frac{1+\frac{2b}{a}\frac{R_{sy}}{R_s}\left(\frac{m\lambda}{2a}\right)^2}{\sqrt{1-\left(\frac{m\lambda}{2a}\right)^2}}$	$\frac{1}{b}\frac{R_s}{R_o}\frac{1+\frac{2b}{a}\left(\frac{m\lambda}{2a}\right)^2}{\sqrt{1-\left(\frac{m\lambda}{2a}\right)^2}}$
TE_{on}	$\frac{1}{b}\frac{R_s}{R_o}\,2\,\frac{1+\frac{b}{2a}\left(\frac{R_{sy}}{R_s}+\left[\left(\frac{2b}{n\lambda}\right)^2-1\right]\frac{R_{sz}}{R_s}\right)}{\left(\frac{2b}{n\lambda}\right)^2\sqrt{1-\left(\frac{n\lambda}{2b}\right)^2}}$	$\frac{1}{b}\frac{R_s}{R_o}\,2\,\frac{1+\frac{b}{2a}\left(\frac{2b}{n\lambda}\right)^2}{\left(\frac{2b}{n\lambda}\right)^2\sqrt{1-\left(\frac{n\lambda}{2b}\right)^2}}$
TE_{mn}	$\frac{1}{b}\frac{R_s}{R_o}\frac{2\left[\left(\frac{m\lambda}{2a}\right)^2+\left(\frac{n\lambda}{2b}\right)^2\right]}{\sqrt{1-\left(\frac{m\lambda}{2a}\right)^2-\left(\frac{n\lambda}{2b}\right)^2}}\left\{1+\frac{b}{a}\frac{R_{sy}}{R_s}+\frac{1-\left(\frac{m\lambda}{2a}\right)^2-\left(\frac{n\lambda}{2b}\right)^2}{\left[\left(\frac{m\lambda}{2a}\right)^2+\left(\frac{n\lambda}{2b}\right)^2\right]^2}\left[\left(\frac{m\lambda}{2a}\right)^2+\left(\frac{n\lambda}{2b}\right)^2\cdot\frac{R_{sz}}{R_s}\frac{b}{a}\right]\right\}$	$\frac{1}{b}\frac{R_s}{R_o}\,2\,\frac{\left(\frac{m\lambda}{2a}\right)^2+\left(\frac{n\lambda}{2b}\right)^2}{\sqrt{1-\left(\frac{m\lambda}{2a}\right)^2-\left(\frac{n\lambda}{2b}\right)^2}}\left\{1+\frac{b}{a}+\frac{1-\left(\frac{m\lambda}{2a}\right)^2-\left(\frac{n\lambda}{2b}\right)^2}{\left[\left(\frac{m\lambda}{2a}\right)^2+\left(\frac{n\lambda}{2b}\right)^2\right]^2}\cdot\left[\left(\frac{m\lambda}{2a}\right)^2+\left(\frac{n\lambda}{2b}\right)^2\frac{b}{a}\right]\right\}$
TM_{mn}	$\frac{1}{b}\frac{R_s}{R_o}\frac{2}{\sqrt{1-\left(\frac{m\lambda}{2a}\right)^2-\left(\frac{n\lambda}{2b}\right)^2}}\;\frac{\left(\frac{m\lambda}{2a}\right)^2+\frac{b}{a}\left(\frac{n\lambda}{2b}\right)^2\frac{R_{sz}}{R_s}}{\left(\frac{m\lambda}{2a}\right)^2+\left(\frac{n\lambda}{2b}\right)^2}$	$\frac{1}{b}\frac{R_s}{R_o}\frac{2}{\sqrt{1-\left(\frac{m\lambda}{2a}\right)^2+\left(\frac{n\lambda}{2b}\right)^2}}\;\frac{\left(\frac{m\lambda}{2a}\right)^2+\frac{b}{a}\left(\frac{n\lambda}{2b}\right)^2}{\left(\frac{m\lambda}{2a}\right)^2+\left(\frac{n\lambda}{2b}\right)^2}$

TABLE I

Attenuation of Propagating Modes in a Waveguide with Anisotropic Walls

conductor only in the term R_{sy}/R_s which, by Equation (34), approaches the limiting value $R_{s1}(w_1 + w_2)/w_2$ as R_{s2} becomes large. In contrast, the attenuation for all the other modes contain the term $R_{sZ}\ R_s$ which simply continues to increase with R_{s2}. The analysis shows that some increase in attenuation for the TE_{m0} modes occurs when the poor-conducting strips are added, but, no more than indicated by the limiting value of R_{sy} given above. The other modes, however, experience a much larger attenuation since the value of R_{sZ} continues to increase with R_{s2}, the surface resistivity of the poor-conducting metal. Inherent in this analysis is the fact that the attenuation is not too great even for those modes which are being suppressed. This is actually desirable in some instances for ultra high power since it avoids excess heating of the mode filter.

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MICROWAVE ASSOCIATES, INC.
BURLINGTON, MASSACHUSETTS

FAILURE MECHANISMS IN ULTRA HIGH POWER TRANSMISSION LINES

Dr. Meyer Gilden

First Technical Note, 19 June 1961 to 19 December 1961

55 pp. - Illus. - Graphs, Air Force Contract AF30(602)-2545

This work treats the failure mechanism in microwave transmission lines at ultra high power levels. Electrical breakdown under non-uniform conditions is discussed. The discussion includes the application of the variational technique for solving the diffusion equation and also includes the derivation of an additional term for the diffusion equation to account for non-uniformities in the gas density. As part of the non-uniform electric field problem, expressions are derived for an idealized rough surface. As part of the more general effects of non-uniform conditions it is shown that a small foreign body in a waveguide can become extremely hot and cause reductions in peak power breakdown thresholds of approximately 5:1. An analysis of the cooling capabilities of an internal gas flow in a waveguide shows that under ~~r~~estricted conditions the power dissipation can be increased by a factor of two or three. Finally the characteristics of a mode suppression filter of oversized, large wave length, rectangular waveguide is derived and discussed.

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BURLINGTON, MASSACHUSETTS

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Dr. Meyer Gilden

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ULTRA HIGH POWER TRANSMISSION LINE TECHNIQUES

Prepared by:

Dr. Meyer Gilden

Approved by:

Dr. Lawrence Gould

MICROWAVE ASSOCIATES, INC.
Burlington, Massachusetts

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